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SOIL CARBON, NITROGEN USE, AND WATER USE AFFECTED BY ROTATION IN THE NORTHERN CORN BELT

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ABSTRACT

Diversified crop rotation may improve production efficiency, reduce fertilizer nitrogen (N) requirements for corn (*Zea mays* L.) and increase soil carbon (C) storage. Objectives were to determine effect of rotation and fertilizer N on soil C sequestration, water use, and N use. An experiment was started in 1990 on a Barnes clay loam (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) near Brookings, South Dakota. Primary tillage on all rotations was with a chisel plow. Rotations were continuous corn (CC), corn-soybean [*Glycine max* (L.) Merr.] (CS) and a 4-year rotation of corn-soybean-wheat (*Triticum aestivum* L.) companion seeded with alfalfa (*Medicago sativa* L.)-alfalfa hay (CSWA). Additional treatments included plots of perennial warm season, cool season, and mixtures of warm and cool season grasses. N treatments for corn were: corn fertilized for a grain yield of 8.5 Mg ha^{-1} (highN), 5.3 Mg ha^{-1} (midN), and no N fertilizer (noN). Average corn grain yield (1996-2001) was not different among rotations at 7.1 Mg ha^{-1} under highN. Corn yield differences among rotations increased with decreased fertilizer N. Average (1996-2001) corn yield with noN fertilizer were 7.3 Mg ha^{-1} under CSWA, 6.1 Mg ha^{-1} under CS, and 3.8 Mg ha^{-1} under CC. Rotation did not improve N use efficiency (NUE) or water use efficiency (WUE) under highN. With midN, NUE and WUE was about 40% greater under CSWA compared with CC. Plant carbon return depended on rotation and N. In the past 10 years, total C returned from above ground biomass were 29.8 Mg ha^{-1} under CC with highN and 12.8 Mg ha^{-1} under CSWA with noN. Soil C in the top 15 cm significantly increased (0.7 g kg^{-1}) with perennial grass cover but decreased (1.7 g kg^{-1}) under CC, CS, and CSWA. C/N ratio significantly narrowed (-0.75) with CSWA and widened (0.72) under grass. Diversified rotations have potential to increase N use efficiency and reduce fertilizer N input for corn. However, within a corn production system using conventional tillage and producing (averaged across rotation and N treatment) about 6.2 Mg ha^{-1} corn grain per year, we found no gain in soil C after 10 years regardless of rotation.

INTRODUCTION

Profit margins for production of most crops are very narrow and producers seek sustainable cropping systems that provide consistent return on investment. Nitrogen has been considered as one of the best crop-input investments that a farmer can make in terms of return on dollars spent. Bundy et al. (1999) estimated that in the 12 states of the North Central United

States, at least 4 million tons of N fertilizer are applied annually to corn at a cost of about 800 million dollars. Thus, there is substantial justification to improve N management in the North Central Region of the USA. Objectives of our research were to determine effect of rotation and fertilizer N on soil C sequestration, WUE, and NUE in the northern Corn Belt.

MATERIALS AND METHODS

Our study was located on the Eastern South Dakota Soil and Water Research Farm near Brookings, South Dakota on a Barnes clay loam with nearly level topography. Whole plots (rotations) in the split plot experiment were arranged as a randomized complete block with three replications. Split plots were N management. All phases of each rotation were present every year.

Crop rotations were: continuous corn (CC), a 2-year rotation of corn-soybean (CS), and a 4-year rotation of corn, soybean, spring wheat, and alfalfa (CSWA). In the 4-year rotation, spring wheat was used as a grain crop and as a companion crop to establish alfalfa. Plots were 30 m long x 30 m wide. Primary tillage since 1996 was with a chisel plow. Two additional treatments were perennial grass and a tillage treatment that used ridge tillage for corn and soybean (CSr). With the exception of primary tillage, the CSr plots were treated as the CS plots. Pikul et al. (2001a, 2001b) provides additional details of this experiment.

Nitrogen treatments were corn fertilized for a yield goal of 8.5 Mg grain ha^{-1} (highN), corn fertilized for a YG of 5.3 Mg grain ha^{-1} (midN), and corn not fertilized (noN). Total soil nitrate was used to estimate fertilizer N prescription for corn (Gerwing and Gelderman, 1996). Nitrogen prescription was met by applying starter fertilizer with the seed and sidedressing with appropriate amounts of urea as 46-0-0 (elemental N-P-K). Starter fertilizer for corn was applied at seeding and placed 5 cm to the side and 5 cm deeper than seed. Starting with the 1996 crop year, 112 kg ha^{-1} of starter fertilizer as 14-16-11, 7-16-11, and 0-16-11 (elemental N-P-K) were applied on highN, midN, and noN plots, respectively. Available N (AN) for the corn crop was defined as mineral sources of available N and NUE was calculated as the ratio of corn grain yield to AN.

Grain yields were measured with a Massey Ferguson MF 8-XP research plot combine (Kincaid Equipment Manufacturing[1], Haven, Kansas) equipped with an electronic weigh bucket. On each plot, 8 rows, 30 m long (1/5 of the plot area) were harvested for grain yield. Corn grain yields were adjusted to 15.5% moisture.

Soil water content was measured using neutron attenuation equipment to determine water storage and use. Neutron equipment was calibrated in a manner described by Pikul and Aase (1998). Water use (WU) was defined as beginning soil water content minus ending soil water content plus precipitation during the growing season. Operationally, this period was defined as 1 June through 30 September. Water use efficiency was calculated as the ratio of corn grain yield to WU.

Soil samples for nitrate-N were collected in the fall to a depth of 120 cm at increments of 0 to 15 cm, 15 to 30 cm, 30 to 60 cm, 60 to 90 cm, and 90 to 120 cm. Three samples were taken randomly from each depth on each plot. Nitrate-N was measured using 2 M KCl extraction and copperized Cd reduction column procedure (Zellweger Analytics, 1992).

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[1] Mention of trade names is for the benefit of the reader and does not constitute endorsement by the U.S. Department of Agriculture over other products not mentioned.

Soil C and N were measured on soil samples collected in 1989 and 2000 using a LECO 2000 C-N analyzer (St Joseph, Michigan). Total C was considered to be total organic C because average (81 plots) soil pH of the top 15 cm was 6.5. Initial field samples (1989) were collected on a 30-m by 30-m grid (Maursetter, 1992).

RESULTS AND DISCUSSION

There was a significant ($p \leq 0.10$) corn-yield response to rotation except for highN. Average corn yield (6 years) under midN (Table 1) was about 36 percent greater on CS and CSWA than corn yield under CC. Under noN, average corn yield (6 years) was about 75 percent greater on CS and CSWA than corn yield under CC. Average yield across all N levels was 7228, 7108, and 5235 kg ha^{-1} for CSWA, CS, and CC respectively.

Table 1. Average (1996-2001) corn grain yield, applied fertilizer N, autumn soil nitrate N, nitrogen use efficiency (NUE), water use efficiency (WUE), and total water use for June through September (Sum of precipitation and soil water extracted from the top 1.8 m).

Rotation and N treatment	Corn yield	N fertilizer applied	Soil NO_3-N	NUE	WUE	Total water use
	----------------	kg/ha	--------------	kg corn/ha/ kg N/ha	kg corn/ha/ mm water	mm
highN						
CC	6451	126	65	35	19	329
CS	7726	131	51	43	22	348
CSWA	7133	123	52	41	21	333
p-value	ns	ns	ns	ns	ns	ns
midN						
CC	5426 b	72	41	49	17 b	315 ab
CS	7462 a	74	39	67	21 ab	352 b
CSWA	7251 a	59	48	70	24 a	306 a
p-value	0.011	ns	ns	0.096	0.089	0.063
noN						
CC	3827 b	0	26 b	162	12 b	314
CS	6136 a	0	40 ab	172	18 a	336
CSWA	7300 a	0	47 a	202	22 a	335
p-value	0.001	ns	0.106	ns	0.001	ns

Corn grain yield response to N within each rotation were significantly different except for the CSWA rotation (Statistical analysis not shown in Table1). Average corn yield (6 years) for highN, midN, and noN within the CSWA rotation was 7.1, 7.3, and 7.3 Mg ha^{-1}, respectively. Under the CS rotation, average corn yield for highN and midN, at 7.6 Mg ha^{-1}, was significantly greater than corn yield for noN (6.1 Mg ha^{-1}). Corn yield response to N fertilizer was significantly different for each N level under CC with yields of 6.5, 5.4, and 3.8 Mg ha^{-1}, for respective fertilizer treatments of highN, midN, and noN.

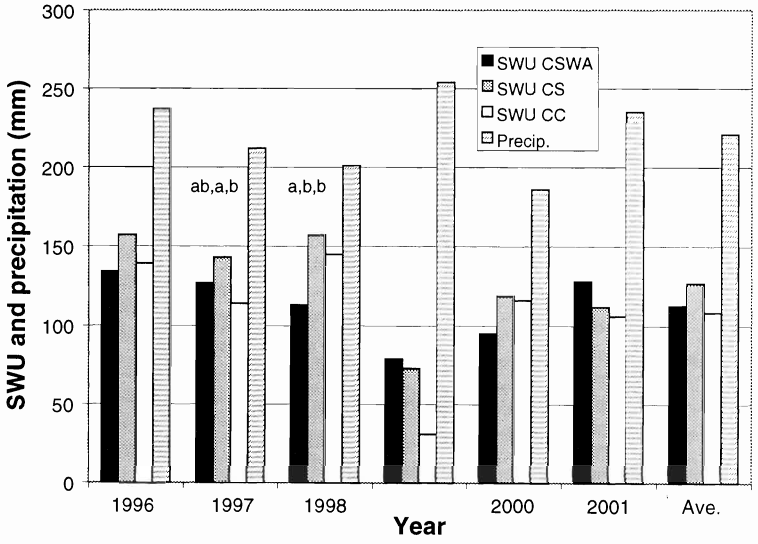
In the past 6 years, there were no differences in N fertilizer applied to rotations within fertilizer treatments (Table 1). In addition there were no significant differences in autumn soil nitrate-N except at the noN fertilizer level (Table 1). Autumn soil nitrate-N was significantly different between CSWA and CC at 47 kg ha^{-1} and 26 kg ha^{-1}, respectively. Consequently, total inorganic-N available to corn (Total of N fertilizer applied and soil nitrate-N, Table 1) was only different among rotations at the noN fertilizer treatment level.

There were significant differences in NUE between rotations only within the midN treatment (Table 1). As applied N decreased, NUE increased. A large NUE value suggests that significant amounts of nitrogen were transformed (mineralized) from organic to inorganic forms during the growing season. Within each N treatment and rotation there was considerable variability in NUE from year to year. For example, under CSWA rotation with noN, greatest NUE was about 450 kg corn ha^{-1} per kg N ha^{-1} in 1997 and least was 92 kg corn ha^{-1} per kg N ha^{-1} in 1999. The lowest NUE was with CC regardless of N level. A simplistic conclusion might be that the overall risk associated with inefficient N use might be minimized by using longer rotations (that include legumes) and reducing fertilizer N application.

We are uncertain if the N treatments used in this study provided for optimum or maximum corn grain yield within each rotation. Within the highN and midN treatments, there has been no difference in the amount of N fertilizer supplied in a given year among rotations (Table 1). In the last 6 years, average available N (fertilizer N and soil nitrate) for the highN treatment was 183 kg N ha^{-1} and 111 kg N ha^{-1} for the midN treatment. Average available N (soil nitrate) was 38 kg N ha^{-1} under noN.

Water and available N are the most important factors that govern yield and one or the other can limit growth. It is commonly known that seasonal evapotranspiration under alfalfa hay may be at least twice that of maize. Corn yield on the CSWA rotation fertilized at highN was significantly reduced in 1998 compared to CC and CS (yield data by year not shown). Alfalfa grown in 1997 extracted more soil water than did corn on CC or soybean on CS and the consequence of this can be seen in Figure 1 for soil water use during the 1998 crop year.

Figure 1. Precipitation and soil water use (SWU) during 1 June through 30 September for corn fertilized for a grain yield of 8.5 Mg ha^{-1} (highN). Soil water use measured in the top 1.8 m.



The CSWA rotation used only 112 mm of soil water in 1998, because there was less soil water in the 1.8 m profile on 1 June 1998. In contrast, soil water use on CC was 145 mm and water use on CS was 157 mm. Average soil water in the top 1.8 m on plots following alfalfa (CSWA) was 376 mm (average of all N treatments) on 1 June. By comparison, average soil water

(CC and CS rotation for all N treatments) in the top 1.8 m was 524 mm. On average, WUE was greater under CSWA and CS, compared with CC, except under highN (Table 1).

We did not find a positive effect of crop rotation on soil C sequestration in any of the plots under conventional tillage. Rotations of CSWA, CS, and CC each lost about 1.7 g C kg^{-1} from the plow layer (Average of all N treatments within each rotation) during 1989-2000 (data not shown). In contrast, corn-soybean rotation under ridge tillage neither gained nor lost carbon and plots under grass cover since 1989 gained about 0.7 g C kg^{-1} in the top 15 cm.

Soil improvement is a slow process and crop yield is a valuable indicator of soil condition. In controlled laboratory soil incubation studies, designed to mimic field conditions during the growing season, we found that soil under CSWA had potential to mineralize about 56 kg ha^{-1} more N than soil under CC (Carpenter-Boggs et al., 2000). Alfalfa in the CSWA rotation has had a positive and beneficial effect on soil condition by narrowing the soil C:N ratio during 1989-2000. The C:N ratio under CSWA has decreased (-0.75) while CS and CC rotations remain unchanged (data not shown). Ratio of soil C:N under perennial grass has increased (0.72).

CONCLUSION

Diversified rotations have potential to increase nitrogen use efficiency and reduce fertilizer N requirements for corn. There is a poor understanding of associated soil C storage related to fertilizer practice and crop rotation. Long-term field experiments provide benchmarks that define quantity of C sequestered in soil and the time frame involved in that sequestration. This experiment was started in 1990. Continuous corn returned about 2.3 times as much plant C to the soil as a 4-year rotation. Under conventional tillage methods, the rate of loss of soil organic C was nearly the same as the rate of C return from above-ground-plant material. The net result after 10 years was a loss of soil C from the top six inches of soil under all rotations receiving conventional tillage. Soil C remained unchanged in a corn-soybean rotation under ridge tillage (a reduced tillage practice). Soil productivity is related to both quantity of soil organic C and N composition. Ratio of C:N narrowed under the 4-year rotation because of an increase in soil organic N. A wider C/N ratio developed under perennial grass. Average corn yield under a 4-year rotation without additional fertilizer N has been greater than the yield attainted under continuous corn fertilized with inorganic N to achieve a grain yield of 8.5 Mg ha^{-1}. Competitive corn production under the 4-year rotation without additional N reflects potential to improve soil productivity without additional N inputs.

Our findings are applicable to other production areas in South Dakota as a guide to estimate reasonable rates of soil organic C accumulation or loss. In respect to corn production, our trials represent average corn production in South Dakota. Average corn grain yield for 1995-1999 was 6.8 Mg ha^{-1} (107.8 bu/acre) for Brookings County and 6.5 Mg ha^{-1} (103.2 bu/acre) for South Dakota (Hamlin and Noyes, 2000). Yield from our plots for 1995-1999 was 6.8 Mg ha^{-1} (108.8 bu/acre). Therefore, the quantity of corn residue returned to the soil of our research plots under CC was representative of an average condition for South Dakota. Sustainability questions aside, continuous corn may appear as a viable way to sequester C because of the large amount of organic material returned to the soil under corn. However, as evidenced by our soil C measurements from 1989-2000, all of the plant C returned annually under conventional tillage was subsequently lost to the atmosphere.

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